

## **Large Fluctuations in Speed on Jakobshavn Isbræ, Greenland**

Ian Joughin  
Jet Propulsion Lab, California Institute of Technology  
M/S 300-235  
4800 Oak Grove Drive  
Pasadena, CA 91109, United States  
818-354-1587 (voice), 818-393-3077 (fax)  
[ian@radar-sci.jpl.nasa.gov](mailto:ian@radar-sci.jpl.nasa.gov)

Waleed Abdalati  
Goddard Space Flight Center  
Mailstop 971.0  
Greenbelt, MD 20771  
301-614-5697  
[Waleed.Abdalati@nasa.gov](mailto:Waleed.Abdalati@nasa.gov)

Mark Fahnestock  
Complex Systems Research Center  
Institute for the Study of Earth, Oceans and Space  
461 Morse Hall  
University of New Hampshire  
Durham, NH 03824  
603-862-5065  
[mark.fahnestock@unh.edu](mailto:mark.fahnestock@unh.edu)

We have assembled an 18-year velocity record for Jakobshavn Isbræ, Greenland. From a 1985 speed of ~7000 m/yr, the glacier had slowed by ~1000 m/yr in 1992, which coincided with independently observed thickening in the early 1990s<sup>1</sup>. The glacier then sped up by ~4000 m/yr between 1997 and 2000, during which time other measurements show rapid thinning<sup>1</sup>. From 2000 to 2003, the glacier's floating ice tongue almost entirely disintegrated, as speed increased to 12,600 m/yr. If the retreat of the ice tongue caused the acceleration, then similar losses of floating ice tongues since the Little Ice Age<sup>2</sup> may explain<sup>3</sup> the current rapid thinning observed for many of Greenland's outlet glaciers<sup>4,5</sup>.

Draining ~6.5% of the ice sheet's area, Jakobshavn Isbræ is Greenland's largest outlet glacier<sup>6</sup>. Because of its contribution to the Greenland Ice Sheet's mass balance, an airborne laser altimeter has surveyed this glacier repeatedly since 1991<sup>7</sup>. When many other glaciers were thinning, these surveys revealed that Jakobshavn Isbræ thickened substantially from 1991 to 1997<sup>5</sup> at elevations less than 1100 m. After 1997, the glacier began thinning rapidly with peak rates of ~15 m/yr<sup>1</sup>.

We used interferometric Synthetic Aperture Radar (InSAR) to measure Jakobshavn Isbræ's velocity in 1992, 1994, 1995, and 2000<sup>8</sup>. We also applied feature-tracking methods to Landsat-image pairs to determine velocity in 2001, 2002, and 2003. Earlier velocity measurements were made using airborne imagery from the summer of 1985<sup>9</sup> and by tracking crevasse displacements in laser-altimeter surveys from 1997<sup>10</sup>.

Figure 1 shows the 1992 and 2000 speeds, illustrating a large speedup by 2000 that extends over much of the fast-moving region. This increase also is visible in plots of the

glacier centerline speed (Fig. 2). Inland of ~40-km, there is no appreciable change over the 18-year period. Closer to the ice front, the 2000-to-2003 speeds increase steadily over time with respect to the relatively stable mid 1990's. From 1985 to 1992, however, the glacier slowed just prior to observed thickening<sup>1</sup>.

Figure 3 shows speeds averaged over 20 locations on the fastest (>5000 m/yr) moving areas (Fig. 1, purple symbols) where there are measurements from 1985<sup>9</sup> and for another set of points (Fig. 1, orange symbols) measured in 1997<sup>10</sup>. The 1985 mean speed was 6680 m/yr, which in 1992 decreased to 5710 m/yr and remained nearly constant until 1997. Between May 1997 and October 2000, the glacier speed reached 9400 m/yr and flowed at about this rate in May 2001. Over the next two months, the glacier speed increased to 10,010 m/yr. By summer 2002, the speed had increased to 11,860 m/yr and then to 12,600 m/yr in spring 2003, which is the last period for which we have velocities.

The mid 1990's slow interval corresponds well with 1991-to-1997 measured thickening<sup>1</sup>. The 1985 calving rate was ~26.5 km<sup>3</sup>/yr<sup>11</sup>, so the nearly 1000 m/yr drop in speed by 1992 suggests an ~4-km<sup>3</sup>/yr discharge reduction. Most of the slowdown occurred over the region moving faster than 1000 m/yr. If we assume thickening was confined to this fast-moving area, then we estimate an ~1-m/yr average thickening, which is consistent with observed rates<sup>1</sup>. The 1985-to-2003 speedup implies a near-doubling in discharge to 50 km<sup>3</sup>/yr. Excluding the former ice tongue's area, this implies an ~6 m/yr average thinning over the fast-moving region, which also is similar to observations<sup>1</sup>. Thus, the speed variations are sufficient to explain the observed elevation changes as dynamic thickening and thinning<sup>1</sup>.

Melt-water input to the bed seasonally affects nearby inland ice speed<sup>12</sup>, but these fluctuations are far smaller than the changes we observe. While we have only coarse intra-annual sampling, our results suggest a trend of increasing speed starting in 2000, rather than a seasonal pattern of summer speed up and winter slow down<sup>12</sup>. Since the speedup appears to persist through the winter, it seems unlikely that increased surface-melt-water input to the bed directly caused the acceleration. Earlier observations that found no seasonal variation on Jakobshavn Isbræ<sup>9,13</sup> support this hypothesis.

From 1850 to 1962<sup>2</sup>, the calving front retreated by ~26 km but stabilized and remained within a 2.5-km-long calving zone from 1962 through the 1990's<sup>14</sup>. In October 2000, this pattern changed when a pattern of progressive retreat began that resulted in nearly the complete disintegration of the ice shelf by May 2003 .

The calving front's multi-decadal stability has been attributed, at least in part, to lateral resistance from the fjord walls that may have yielded a restraining "back-stress" on the floating ice with an influence extending above the grounding zone<sup>3,6</sup>. Several of the speed increases coincide with losses of sections of the ice tongue as it broke up. Satellite images also indicate that several large rifts began developing in 2000 along the fjord's northern wall, which may have reduced lateral resistance. Thus, back-stress reduction from the ice tongue's disintegration may have caused or contributed to the speedup. This is consistent with observations elsewhere of acceleration following ice shelf loss<sup>15,16</sup>.

If the ice tongue's weakening and retreat caused the speedup, then it is not clear what initiated the retreat after a period of multi-decadal stability<sup>14</sup>. At nearby Egedesminde, the 1998-to-2001 melt intensity was abnormally high<sup>1</sup> and passive

microwave data indicate a high melt 2002 extent. Calving rates are higher in summer<sup>14</sup>, indicating a sensitivity to temperature/melt<sup>3,17,18</sup>. Thus, increased calving may have forced the ice tongue to retreat beyond its stable position to initiate the acceleration.

Jakobshavn Isbræ's acceleration and near-doubling of ice discharge is noteworthy because this single glacier has increased the rate of sea-level rise by  $\sim 0.06$  mm/yr, or  $\sim 4\%$  of the 20<sup>th</sup> century rate<sup>19</sup>. This speedup is the most striking of several ice-stream and outlet-glacier speedups and slowdowns observed with just over a decade of spaceborne InSAR measurements<sup>20-23</sup>. Collectively, these observations indicate that fast-flowing glaciers can significantly alter ice-sheet discharge at sub-decadal time scales and that their response to climate change has at least the potential to be rapid. This argues both for improved monitoring of ice sheet mass balance and improved incorporation of fast flow features into ice sheet models, many of which predict century-to-millennial-scale response times<sup>24</sup>.

## Methods

The 1992, 1994, 1995, and 2000 velocity estimates were determined using speckle-tracking over a variety of intervals ranging from 1 to 24 days and an established set of algorithms<sup>8</sup>. Random errors on individual measurements could be as large as a few hundred m/yr (see Fig. 2), but the errors on the averages (e.g., Fig. 3) are well below 100 m/yr. We did not apply any tide correction to the speckle-tracked data, which could yield a nearly-constant velocity bias on the floating ice that would not spatially average out. To assess the impact of this error, we generated velocity estimates from five different interferometric pairs in 1992, each with different tidal errors. The standard deviation for the five individual observations is 69 m/yr. Some of our estimates (1992 and 1994) were

derived by temporally averaging results from multiple (2 to 5) pairs from the same year, which further reduces this error. The 2001 through 2003 estimates were derived using the IMCORR<sup>25</sup> feature-tracking software applied to Landsat image pairs with intervals varying from 16 to 64 days.

Established methods<sup>26</sup> were applied to passive microwave data to determine the 2002 melt extent.

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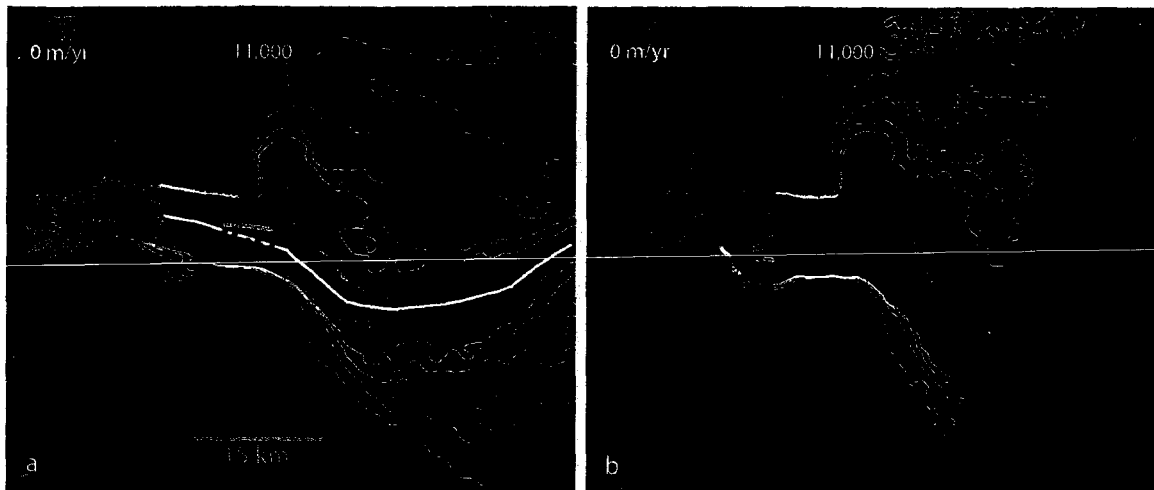
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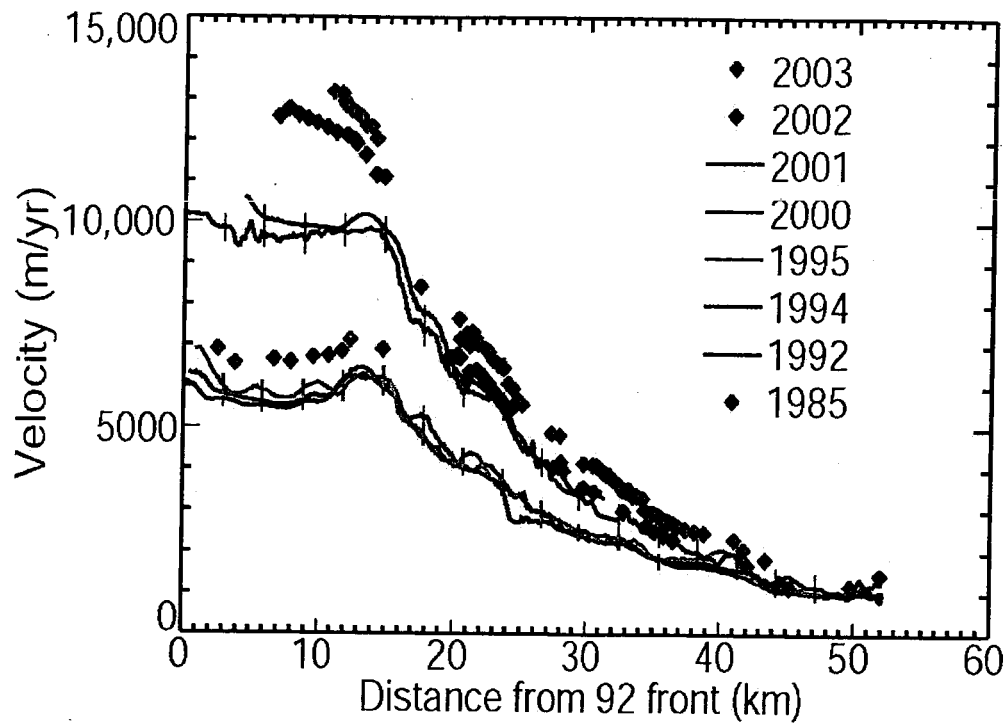
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**Figure 1. Ice flow speed as color over SAR amplitude imagery of Jakobshavn Isbræ in a) February 1992 b) October 2000. In addition to color, speed is contoured with thin black lines at 1000 m/yr intervals and with thin white lines at 200, 400, 600, and 800 m/yr. The thick white line shows the location of the profile plotted in Figure 2. The locations of velocity measurements made in 1997 (orange symbols) and 1985 (purple symbols) are also shown.**



**Figure 2. Profiles of speckle-tracked, Landsat, airborne feature-tracked speed from along the line shown in Figure 1a. One-sigma error bars (black) are shown at several-kilometer intervals. The 1985<sup>9</sup>, 2002, and 2003 data sets were sparsely sampled, so only individual point measurements are plotted. The data were acquired over the periods from February-to-March 1992, December-1993-to-March 1994, November 1995, October-to-November 2000, May 2001, July-to-September 2002, and March-to-May 2003.**

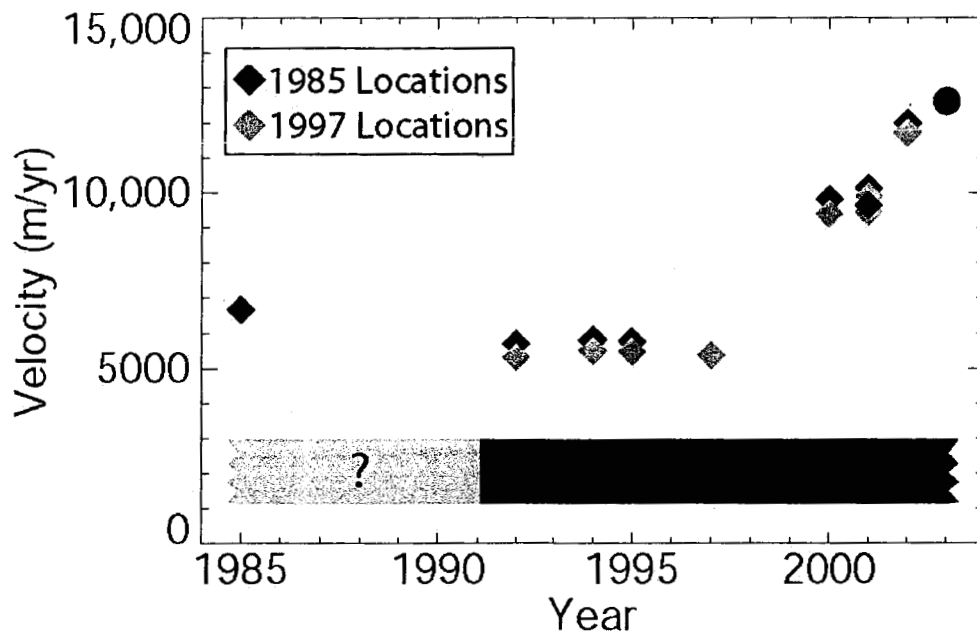


Figure 3. Average speeds verses time for locations coincident with 1985 and 1997 airborne survey locations (see same-color symbols in Figure 1). The slower two points from 2001 were determined using a May-4-to-May-20 pair, while the faster two points are from a May-20-to-July-7 pair. Periods of thickening and thinning were determined from laser altimeter surveys<sup>1</sup>. Minor speed differences for 1985 and 1997 locations reflect differences in the areas sampled. Since much of the floating ice tongue was missing in 2003, the speed for this year (circle) is an average of a subset of points on the remaining ice.